$$+(4\nu-3)\frac{\alpha r^2}{R^2}+\left(\frac{1}{r^2}-\frac{1}{R^2}\right)\frac{\alpha r_o^{\,2}}{\beta}+\alpha(1-2\nu)-4(1-\nu)\Big\} \quad (4.9)$$

or

$$\mathrm{EFL}=\mathrm{EFL}_o+\frac{\sigma_{wo}\,(1-\nu^2)}{E(t,T^o)}-\frac{\sigma_{wo}}{E(t,T^o)}\,\frac{(1+\nu)}{4}\left\{\left[(1-2\nu)+\frac{r_o^{\,2}}{\beta r^2}\right]\left(\frac{\alpha r_o^{\,2}}{\beta R^2}-2\right)Ln\frac{\beta R^2-r_o^2}{\beta r^2-r_o^2}+\right.$$

$$\left.+(4\nu-3)\frac{\alpha r^2}{R^2}+\left(\frac{1}{r^2}-\frac{1}{R^2}\right)\frac{\alpha r_o^{\,2}}{\beta}+\alpha(1-2\nu)\right\}. \quad (4.10)$$

As can be seen from equations 4.8 and 4.9, EFL can be considered as a difference between the initial EFL (before reeling) and a strain on the reel. Also, the strain on the reel is a product of the initial tensile strain (initial stress divided by time- and temperature-dependent modulus of elasticity), shown as the term underlined in a solid line, and a reeling function, shown as the term underlined in a dashed line. These quantities depend on the Young's modulus, Poisson's ratio, relative stiffness of the buffer tube and reel core, and decay rate in the take-up tension. Poisson's ratio represents the degree of coupling between the circumferential and radial stresses. The expression for EFL can be rearranged, according to Equation 4.10, to show the contribution from the bending stiffness per unit area or unit thickness, $E/(1-\nu^2)$, and the stretching stiffness that is proportional to Young's modulus.

Several experiments revealed that when subjected to constant tension, thermoplastic materials exhibit a monotonic reduction in the Young's modulus apparently due to

reorientation of molecular chains. For thermoplastic buffer tube materials, the reduction in the Young's modulus was as large as two times. Numerical computations performed using *Mathematica*®, and Equation 4.10 revealed that the depth of the EFL "parabola" increases with a decrease in Young's modulus.

The time factor and long-term stretching of buffer tubes influence not only Young's modulus, but also creep and shrinkage behavior of the tubes. For high line speeds, buffer tubes are subjected to tension (before the reeling stage) for a shorter duration. Consequently, elongation of thermoplastic materials are smaller than that for lower line speeds. As a result, the EFL obtained for high-speed lines are above that obtained for lower-speed lines.

Typically, an increase in the line speed is associated with a shorter time to cool the buffer tube in the cooling system 381 (because the tube T is passing through a cooling apparatus 381 quicker). See Figure 38. Consequently there is an increased temperature of the reeled buffer tube after manufacture that in turn results in residual shrinkage in addition to that caused by the other residual forces experience while on the reel and during reeling. However, elongation of the reeled material under existing residual tension (circumferential stress) is generally more significant than the shrinkage of thermoplastic materials while cooling. The action of circumferential stresses can be related to the creep of thermoplastic materials. Reeled material under circumferential stress can undergo a certain amount of elongation, thus reducing the level of stresses. To some extent, a longer amount of time on the reel produces lower EFL. Consequently, creep as a function of the time spent on the reel can also be used with the present invention to adjust (reduce) EFL to the desired level.

Also, as discovered in a second embodiment of the present invention, variations in the line speed and the corresponding variation in angular velocity ("ω") of the reel produce a

variation in temperature and tensile load through the radius of the buffer tube roll. In this embodiment, a monotonically variable angular velocity of the spool is used to control the stress state in the buffer tubes, and subsequently the EFL distribution. It should be noted that it is preferred to use the monotonically variable angular velocity of the spool of this embodiment with a stiffness-compliant pad on the reel core to achieve a substantially even EFL distribution. This will be discussed in more detail below.

Examples of two possible monotonically variable curves for the angular speed of the spool are shown in Figure 10. The curves shown 103 and 104 represent two out of many possible monotonically variable curves for angular velocity. It is noted that the exact shape of the monotonically variable curves will depend on several factors including material properties of the reeled material and spool, additional variation in take-up tension, and stiffness of pad(s) used, and is to be adjusted for each individual manufacturing line. For a typical case of a regular rigid (steel) spool core, the curve 104 in Figure 10 is proposed (but any similar curve may be used), while if a pad is used on the spool the curve 103 is proposed. Initially, the angular velocity of the spool monotonically increases. This increase produces monotonically increased take-up tension. As a result, the buffer tube elongates, from a small level at the beginning of the tube to a higher level, causing corresponding changes in the EFL levels, from higher to lower. Because of this, the left side of initial EFL parabola (dashed curve representing an EFL for constant velocity spooling) turns down as shown by arrow 101.

Further, in the preferred embodiment, the ramping rate of angular velocity of the reel, or spool, slows down to produce smaller take-up tension and to increase the EFL. This is shown in Figure 10 by arrow 102. This slow-down step is especially important for the